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1 Determining the 3-D geometry of a dike swarm and its
2 impact on later rift geometry using seismic reflection data

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7 **ABSTRACT**

8 Dike swarm emplacement accommodates extension during rifting and large
9 igneous province (LIP) formation, whereas ancient dike swarms can localize strain during
10 later tectonic events. Deciphering three-dimensional (3-D) dike swarm geometry is
11 critical to accurately calculating magma volumes and magma-assisted crustal extension,
12 allowing syn-emplacement mantle and tectonic processes to be interrogated, and for
13 quantifying the influence ancient dike swarms have, post-emplacement, on faulting.
14 However, the 2-D nature of Earth's surface, combined with the difficulties in imaging
15 sub-vertical dikes on seismic reflection data, and the relatively low resolution of
16 geophysical data in areas of active diking, means that our understanding of dike swarm
17 geometry at depth is limited. We examine an ~25-km-wide, >100-km-long, west-
18 southwest-trending dike swarm imaged, due to post-emplacement rotation to shallower
19 dips, in high-quality 2-D and 3-D seismic reflection data offshore southern Norway.
20 Tuned reflection packages correspond to thin (<75 m thick), closely-spaced dikes. These
21 data provide a unique opportunity to image and map an ancient dike swarm at variable
22 structural levels. Cross-cutting relationships indicate emplacement occurred in the Late

Carboniferous-Early Permian, and was linked to the formation of the ca. 300 Ma Skagerrak-centered LIP. Dike swarm width increases with depth, suggesting that magma volume and crustal extension calculations based on surface exposures are dependent on the level of erosion. During the Mesozoic, rift-related faults localized above and exploited mechanical anisotropies within the dike swarm. We demonstrate that seismic reflection data are a powerful tool in understanding dike swarm geometry and the control of dikes on subsequent faulting.

INTRODUCTION

Dike swarm emplacement facilitates magma transport over significant vertical and lateral distances (e.g., Ernst and Buchan, 1997; Torsvik et al., 2008) and accommodates extension, particularly during large igneous province (LIP) formation and magma-rich continental breakup (e.g., Kendall et al., 2005; Keir et al., 2006). Furthermore, following emplacement and solidification, dike swarms form mechanical anisotropies within the crust, serving to localize strain during later tectonic events (e.g., Dineva et al., 2007). Dike swarms thus influence the syn- and post-emplacement tectonic evolution of many regions, leading numerous studies to (1) use their plan-view geometry and distribution to calculate melt volumes and extension associated with rifting and LIP emplacement, and thus infer mantle and tectonic processes (e.g., Halls, 1982); and (2) further understand rift evolution through correlating their location and geometry to that of later-formed structures (e.g., Dineva et al., 2007). However, because the two-dimensional (2-D) nature of the Earth's surface only allows us to effectively investigate horizontal slices through dike swarms, we do not know whether dike swarm geometry varies with depth, or how, if at all, dike swarms influence the development of younger tectonic

structures. Geophysical and geodetic data (e.g., interferometric synthetic aperture radar) capturing transient ‘diking’ events can provide insight into the 3-D geometry of individual dikes (e.g., Wright et al., 2006; White et al., 2011), but we typically rely on extrapolating surface or near-surface observations to depth to infer 3-D dike swarm structure (e.g., Kavanagh and Sparks, 2011).

Reflection seismology provides one of the only data sets that can constrain both the down-dip and along-strike geometry of dikes, as well as that of overlying structures, across broad areas (e.g., Malehmir and Bellefleur, 2010; Wall et al., 2010). While previous seismic-based studies have imaged or contain evidence of one or several dikes, which may or may not be part of a dike swarm (e.g., Zaleski et al., 1997; Malehmir and Bellefleur, 2010; Wall et al., 2010), we present, to the best of our knowledge, the first seismic data set that images and constrains the geometry of a dike swarm. We identify a 100-km-long, 25-km-wide, and 3-km-high section of a dike swarm in 2-D and 3-D seismic reflection data offshore southern Norway, which consists of numerous, closely spaced dikes that are imaged because the swarm has been rotated post-emplacement and now dips at $\sim 50^\circ$ (Fig. 1a). These data present a unique and exciting opportunity to examine dike swarm geometry with depth and quantitatively assess how the dike swarm influenced the development of a younger, overlying normal fault array.

GEOLOGICAL SETTING

The east-trending Farsund Basin is located just offshore southern Norway (Fig. 1a). The basin defines a south-dipping half-graben, with the southern margin delineated by the Carboniferous-Permian Fjerritslev fault system (Figs. 1b and 1c) (e.g., Mogensen and Jensen, 1994). Reactivation of this fault during Late Jurassic-to-Early Cretaceous

extension caused flexure in its hanging wall (Fig. 1c) (Mogensen and Jensen, 1994). Nearby wells (Fig. 1a) penetrate down to Lower-Middle Permian strata, which likely overlies Permian-Carboniferous strata. We interpret the deepest horizon that can confidently be mapped within our seismic data as the ca. 290–270 Ma Saalian-Altmark unconformity (Figs. 1b and 2a) (Glennie, 1997).

DATASET AND METHODOLOGY

Our main data set is a pre-stack time-migrated, 2-D seismic reflection data set consisting of <5-km-spaced, north-trending seismic sections with a total line length of 2158 km. We also use several other time-migrated 2-D data sets, and a time-migrated, ~500 km² 3-D data set in the west of the study area (Fig. DR1 in the GSA Data Repository¹). The 2-D data image to at least 7 s two-way time (TWT) (~15 km), and the 3-D volume to 4 s TWT (~7 km). Seismic horizon age is constrained by boreholes, the deepest of which terminates in basement below Permian strata (Well 11/5–1; Fig. 1a); no boreholes penetrate the interpreted dike swarm. We performed quantitative analyses, in the form of throw-depth plots (see the Data Repository), on a number of stratigraphically younger faults that are spatially correlated to the underlying dike swarm.

DIKE SWARM SEISMIC CHARACTER

We observe a series of inclined (apparent dips of ~35–50°N), north-dipping, high-amplitude reflections along the northern margin of the Farsund Basin within an ~25-km-wide by ~100-km-long, west-southwest-trending zone (Figs. 1 and 2). Inclined reflections in the swarm center are truncated by the overlying Saalian-Altmark and Base Zechstein unconformities (Fig. 2). These reflections are confidently interpreted between ~0.8–2.5 s TWT (~1–4 km), below which image quality deteriorates, although they

92 appear to continue to greater depths (Figs. 1c and 2). To the west and south, the inclined
93 reflections are deeper (>2.5 s TWT) and relatively poorly imaged (Fig. 1c); mapping of
94 the reflections further east is not possible due to a lack of data. The density of inclined
95 reflections changes across the width of the zone, from ~ 10 reflection peaks/km in the
96 center, to ~ 6 peaks/km at the margins (Fig. 2a). The upper tips of many of the reflections
97 at the margins terminate at stratigraphically lower levels than those in the center (Figs. 1b
98 and 2a); the width of the reflection package thus increases with depth, from ~ 12 km at the
99 Saalian-Altmark unconformity down to ~ 20 km where image quality deteriorates.

100 The inclined reflections may represent a number of different features, including
101 geophysical processing-related artifacts, tilted sedimentary strata, fault-plane reflections,
102 or dikes. We dismiss the first three hypotheses because the inclined reflections (1) are
103 imaged within several 2-D and 3-D seismic surveys, which have different acquisition and
104 processing parameters (see Table DR1 in the Data Repository), implying they are not
105 geophysical (e.g., processing or acquisition) artifacts; (2) do not resemble reflections
106 overlying in the cover, or adjacent inclined reflections (Fig. 2a), suggesting they are not
107 seismic multiples; (3) cross-cut south-dipping (~ 10 – 20° S) reflections associated with
108 Carboniferous-Permian strata, implying they themselves do not represent sedimentary
109 layers (Fig. 2a); and (4) rarely offset the Carboniferous-Permian stratigraphic reflections,
110 indicating that most do not represent fault-plane reflections (Fig. 2). As a result, we favor
111 the interpretation that the majority of the inclined reflections represent dikes, and refer to
112 the overall package as the ‘Farsund Dike Swarm.’ As the dike swarm cross-cuts probable
113 Carboniferous-Permian (<320 Ma) strata and is itself truncated by the 290–270 Ma

114 Saalian-Altmark unconformity (Fig. 2a), we infer an emplacement age of ca. 320–270
115 Ma.

116 Having established the inclined reflections likely represent dikes, we compare our
117 observations of dike swarm geometry across an extensive depth range (~1–3 km), to
118 field- and modeling-based studies reliant on 2-D plan-view exposures (Kavanagh and
119 Sparks, 2011; Bungler et al., 2013). The vertical resolution (i.e., $\lambda/4$, where λ is the
120 seismic wavelength) of the seismic data dictates the maximum (i.e., vertical) thickness of
121 individual dikes for which both margins can be fully resolved, while the thinnest
122 detectable dikes will typically have a vertical thickness of $\lambda/30$ (Slatt, 2006); these
123 parameters can be calculated from the seismic frequency (~20 Hz) and velocity of the
124 interval of interest. Because we have no well data to constrain the seismic velocity of the
125 dike rocks and do not know the ratio of igneous to sedimentary material, we use a range
126 of seismic velocities from 6 km/s (i.e., purely igneous material; Smallwood and Maresh,
127 2002) to 3 km/s (i.e., negligible igneous material) to conduct our depth conversion. These
128 velocities imply that the dike dip is between 35 and 50°. We calculate vertical resolutions
129 of 37.5–75 m and detection limits of 5–10 m. The Farsund Dike Swarm is composed of
130 tuned reflection packages, indicating multiple, relatively thin (<75 m), and closely spaced
131 dikes. We cannot determine whether each package represents interference between
132 reflections arising from the margins of one or several dikes; as a result, we cannot assess
133 detailed dike spacing or thickness. The lateral distance between inclined reflections,
134 perhaps a proxy for dike spacing, does, however, appear to increase toward the margins,
135 where the majority of dikes terminate at deeper stratigraphic levels than those in the
136 swarm center (Fig. 2a). This inverse relationship is inconsistent with analytical model

137 predictions, which suggest spacing increases with dike height (cf. Bunger et al., 2013), it
138 is plausible that dike swarm emplacement was relatively protracted, with younger dikes
139 preferentially intruded into the center of the swarm, thereby reducing spacing.

140 The observation that dike height varies across the swarm (Fig. 2) further indicates
141 that dikes exposed in plan-view at the Earth's surface may not represent true dike swarm
142 width, and could significantly influence magma volume and associated extension
143 calculations. For example, assuming a 1:1 dike to host rock ratio, a swarm length of 50
144 km, and a dike height of 3 km, dike swarm volumes calculated from the measured widths
145 at the Saalian-Altmark unconformity (i.e., 12 km) and a deeper level (e.g., 20 km) would
146 be 900 km³ and 1500 km³, respectively, with associated extension measurements of 6 and
147 10 km respectively.

148 **TECTONO-MAGMATIC CONTEXT AND SIGNIFICANCE OF THE FARSUND**

149 **DIKE SWARM**

150 The west-southwest–trending, Late-Carboniferous-to-Early Permian (emplaced
151 between 320 and 270 Ma) Farsund Dike Swarm is contemporaneous with a 300–280 Ma
152 phase of dike emplacement and volcanic activity across Central and Northern Europe (see
153 Torsvik et al., 2008, and references therein). Paleogeographic reconstructions indicate
154 that onshore dikes intruded during this magmatic event are distributed radially about the
155 Skagerrak-centered LIP (ScLIP; Fig. 3) (Torsvik et al., 2008). We suggest that the
156 Farsund Dike Swarm links to the Midland Valley Dike Suite in the United Kingdom,
157 forming a proximal part to a >1000-km-long, western arm of a trilete radial dike swarm
158 laterally injected from the ScLIP (Fig. 3).

159 **DIKE-FAULT INTERACTIONS**

A series of north-dipping, Mesozoic faults overlie and link with the Farsund Dike Swarm (Figs. 1b and 2). Kinematic analysis (see supplementary information) identifying the site of maximum throw indicates these faults nucleated at or just above the top of the dike swarm (Fig. 2d). Large negative throw gradients present around the Top Jurassic possibly indicate erosion at this time, being overlain by a low-throw segment that is indicative of fault reactivation (Fig. 2d) (e.g., Cartwright et al., 1998). The faults likely initiated in the Triassic in response to margin flexure; reactivation occurred due to slip on and associated hanging wall flexure of the Fjerritslev Fault during Late Jurassic-Early Cretaceous extension (Fig. 4) (Mogensen and Jensen, 1994). This flexure rotated the Farsund Dike Swarm, allowing it to be imaged in seismic data (Fig. 4). Overall, weaknesses within the dike swarm (e.g., dike contacts) localized rift-related strain and were exploited by these later formed faults.

CONCLUSIONS

We present images of one of the first dike swarms to be imaged in seismic reflection data. The swarm trends west-southwest, is 25 km wide, and is constrained to at least ~3 km depth. Seismic-stratigraphic and geometric constraints link the swarm to the ca. 300 Ma ScLIP, and show that it forms, along with the Midland Valley Dyke Suite, part of an ~1000-km-long system across the North Sea. Post-emplacement, regional faulting rotated the swarm to ~50° dip, allowing its imaging on seismic reflection data. By imaging the dike swarm in cross-section, we highlight a variable dike swarm width with depth. This observation is not possible based on plan-view sections at the Earth's surface alone and shows how calculations of crustal extension and magma volumes may be dependent on the level of erosion of the dike swarm. We show that normal faults later

exploited internal mechanical anisotropies between individual dikes. Our imaging of a dike swarm at depth offers new insights into their geometry, and implications for their role in continental extension, in addition to showcasing how dike swarms can influence tectonic events after their emplacement.

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264 **FIGURE CAPTIONS**

265 Figure 1. A: Two-way travel time structure map of the Base Zechstein (Upper Permian)
266 surface showing the extent of the Farsund Dike Swarm. Areas of high and low
267 confidence interpretation are shown in dark gray and light gray, respectively, based upon
268 the clarity of the steeply inclined reflections. B: Stratigraphic column detailing mapped
269 horizons and regional tectonics. C: Interpreted regional seismic section. Some dikes are
270 highlighted in green, although the majority are uninterpreted. Seismic data are shown

using the Society of Exploration Geophysicists reverse polarity convention. See the Data Repository (see footnote 1) for uninterpreted section.

Figure 2. A: Interpreted seismic section showing dike swarm seismic character, and stratigraphic and fault relationships. B, C: Seismic sections showing dike seismic character within interpreted swarm. D: Throw-length profiles for the faults highlighted in Figures 1A and 2A. See Figure 1A for figure locations. See the Data Repository (see footnote 1) for uninterpreted sections.

Figure 3. Location of the Farsund Dike Swarm in relation to the regional Skagerrak-centered LIP. Dikes and volcanic outlines follow Heeremans et al. (2004). Ages from Torsvik et al. (2008), and references therein).

Figure 4. Schematic evolution of the dike swarm. Dike emplacement occurs during the Permian-Carboniferous, before Early Cretaceous fault activity to the south causes rotation of the hanging wall, allowing imaging of the dike swarm and associated flexural faulting.

¹GSA Data Repository item 2018xxx, xxxxxxxx, is available online at <http://www.geosociety.org/datarepository/2018/> or on request from editing@geosociety.org.

294 **Appendix A – Throw-depth analyses**

295 T-z profiles can elucidate the kinematic history of normal faults (i.e. fault nucleation, growth, and/or
296 reactivation) and thereby the tectonic evolution of sedimentary basins (see Mansfield and Cartwright, 1996;
297 Cartwright et al., 1998 for a full description of the methods used). To assess how the Farsund Dike Swarm
298 may have influenced the post-emplacement evolution of the study area, we calculated throw-depth (T-z)
299 profiles along a number of key faults. We measure the hanging wall and footwall cut-offs of multiple
300 stratigraphic horizons along the faults, plotting the calculated throw at the mid-point between the cut-offs.
301 To accurately constrain the evolution of a fault, all fault slip-related strain must be explicitly recorded; i.e.
302 we must incorporate both ductile (e.g. folding) and brittle (e.g. faulting) components of the strain field
303 associated with fault slip (e.g. Meyer et al., 2002; Long and Imber, 2010; Whipp et al., 2014; Duffy et al.,
304 2015; Jackson et al., 2017). Where fault-parallel folding occurs, hanging wall and footwall cut-offs were
305 defined by projecting the regional dip of the horizon of interest, as measured some distance away from the
306 fault, onto the fault plane.

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327

Figure 1.

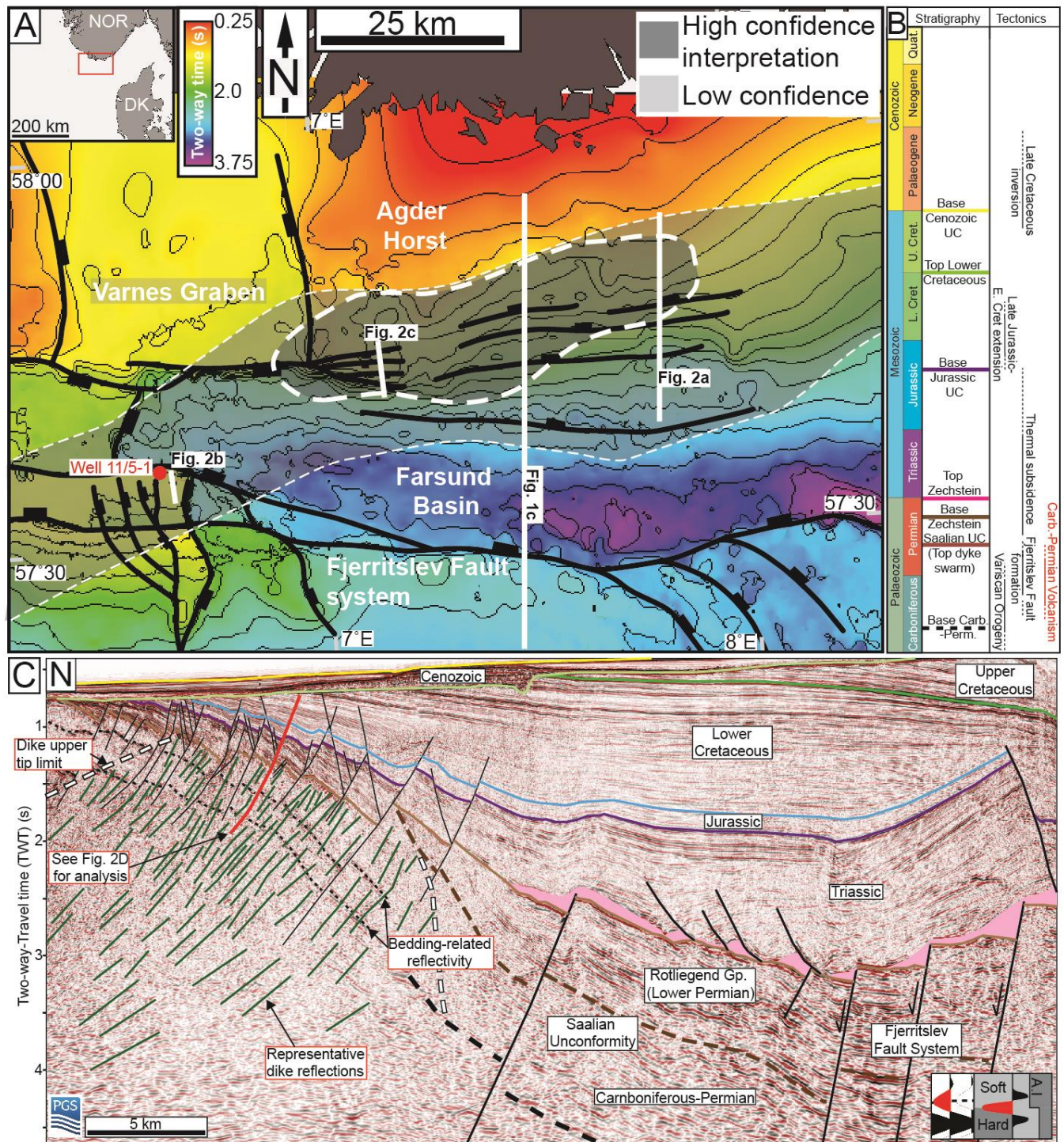


Figure 2.

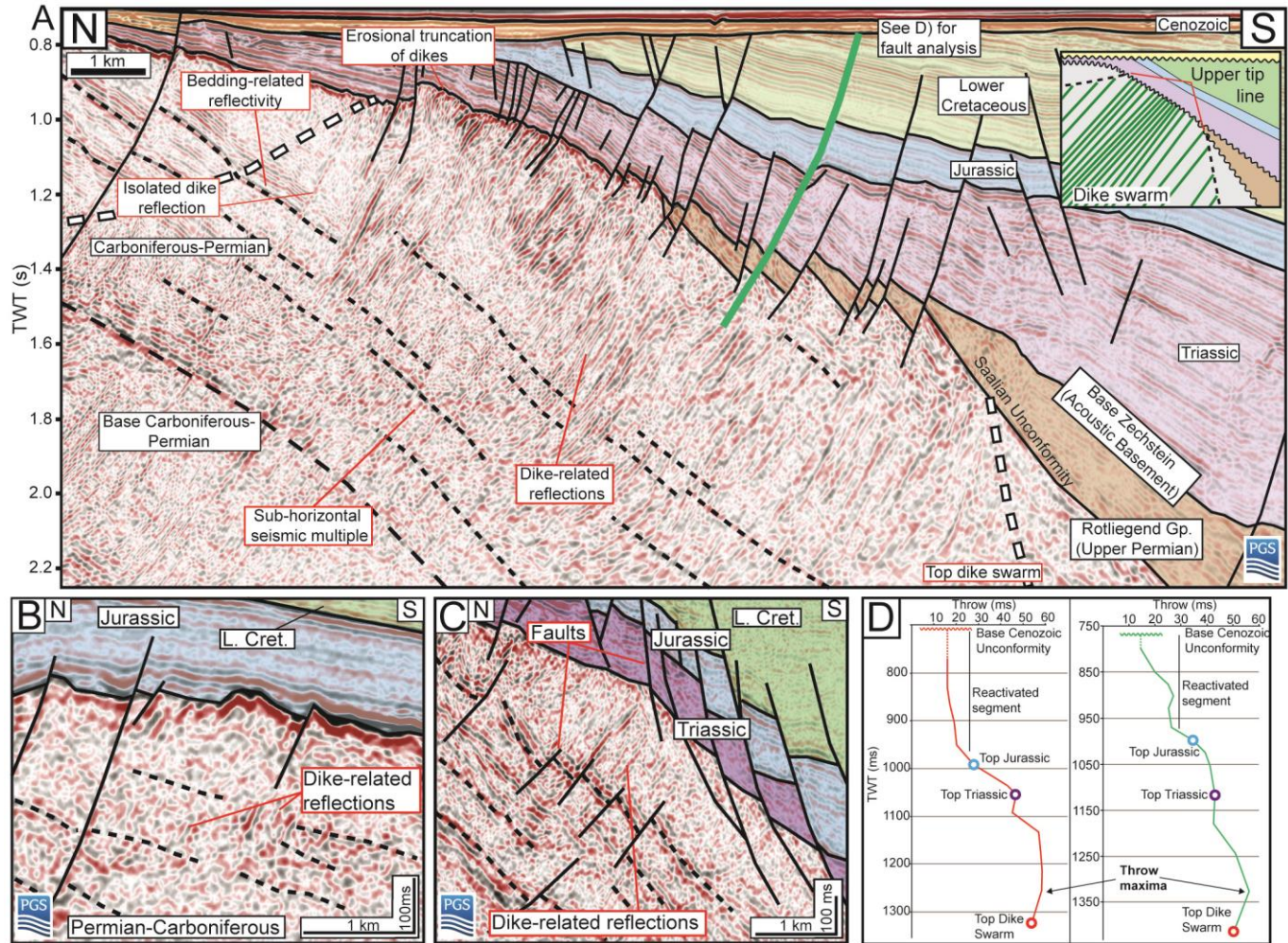
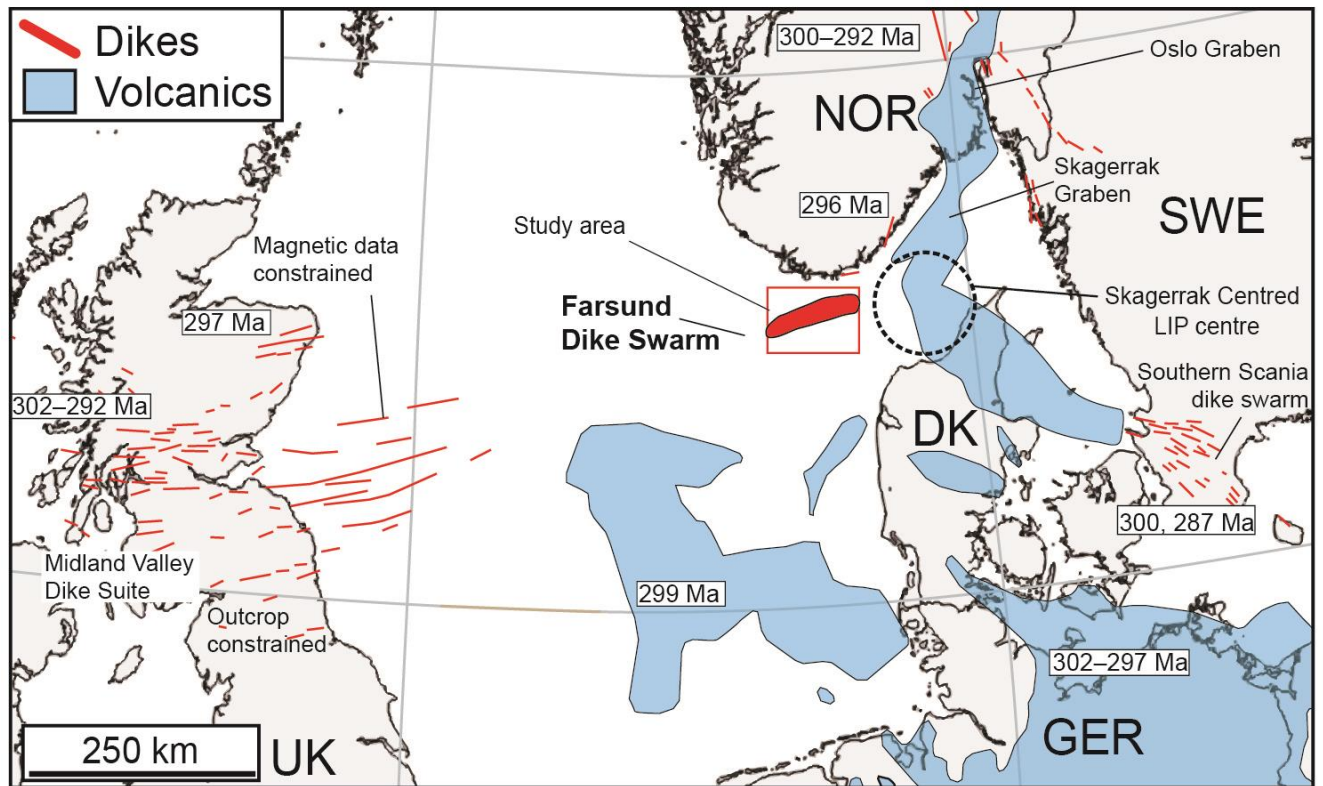
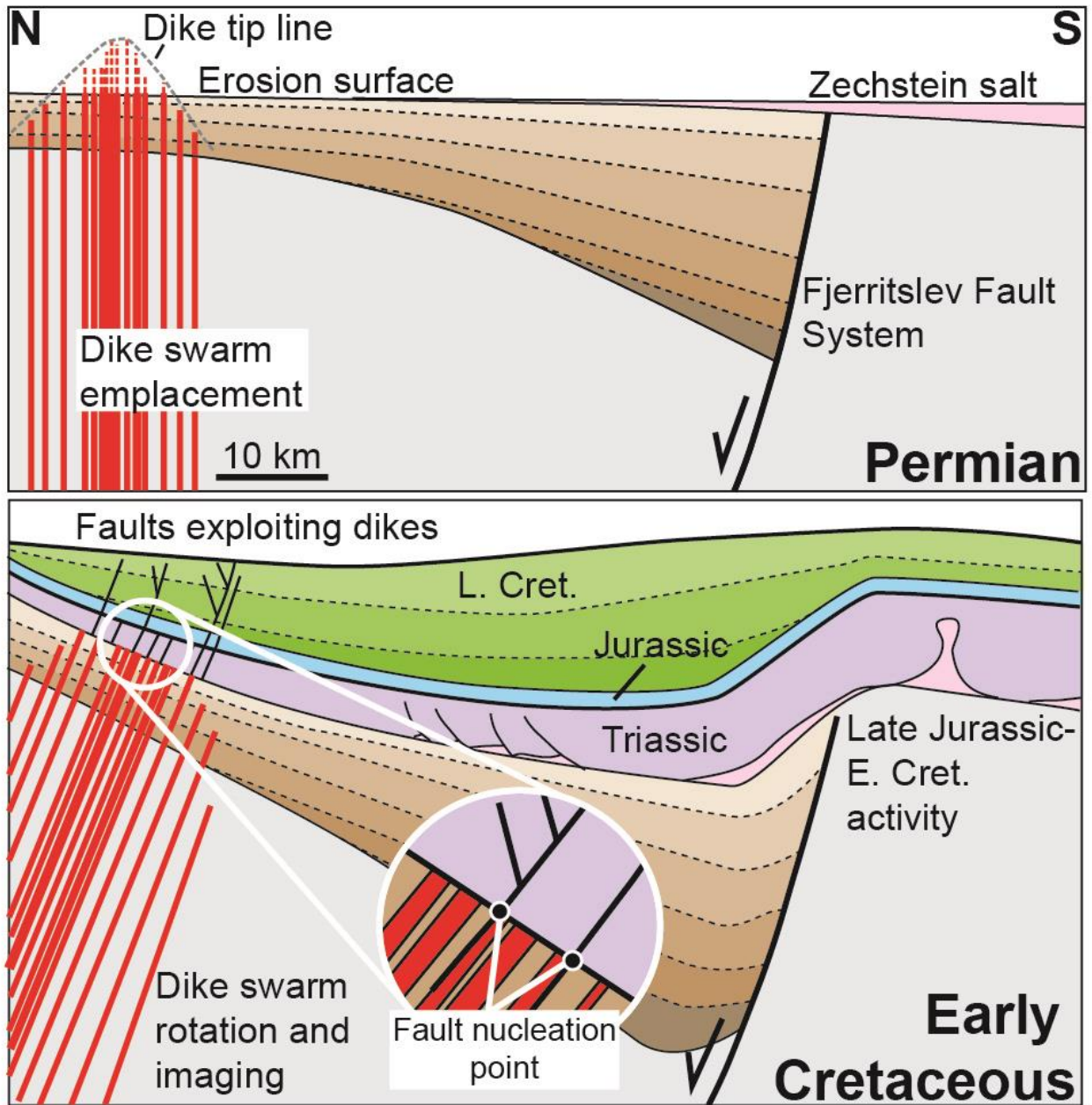


Figure 3.

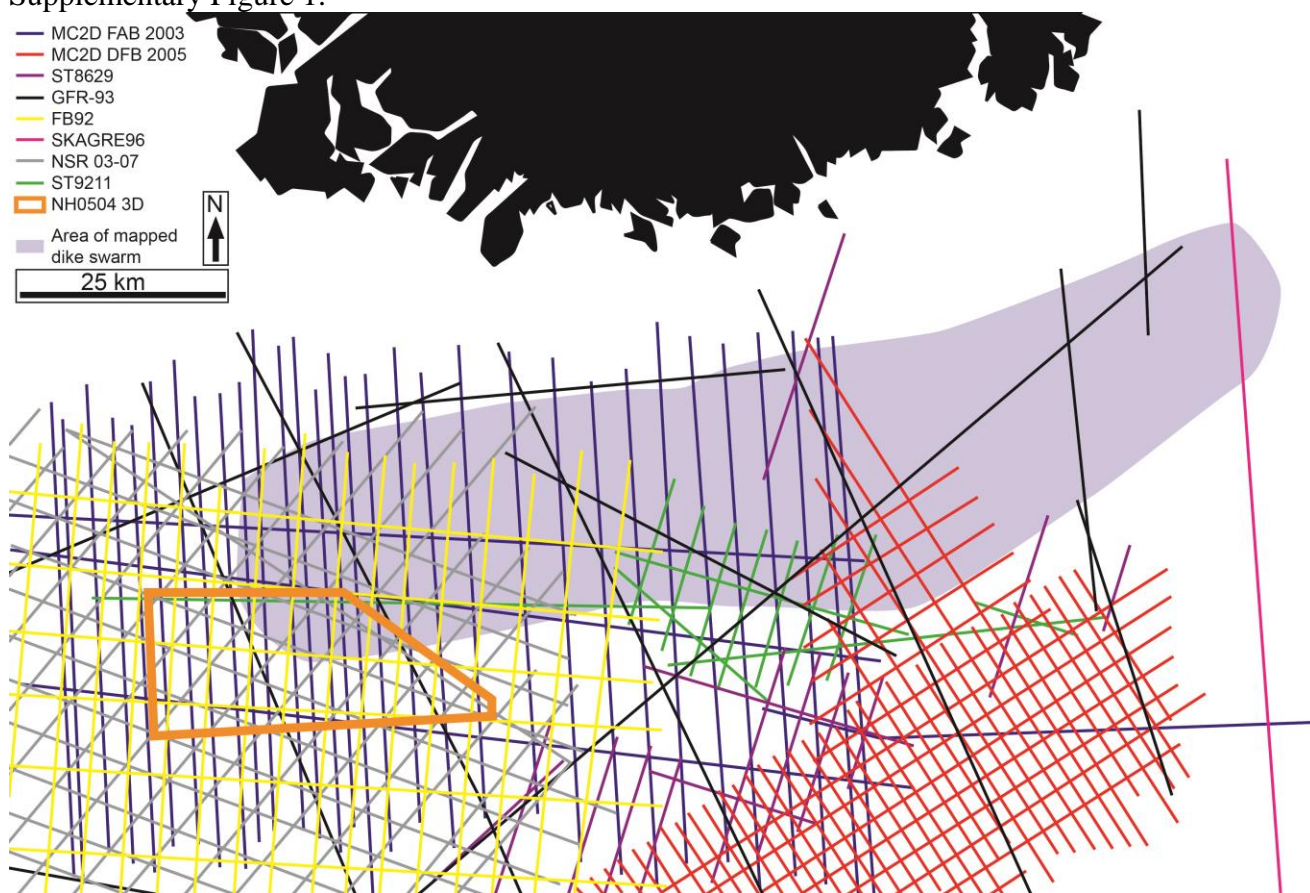


342 Figure 4.



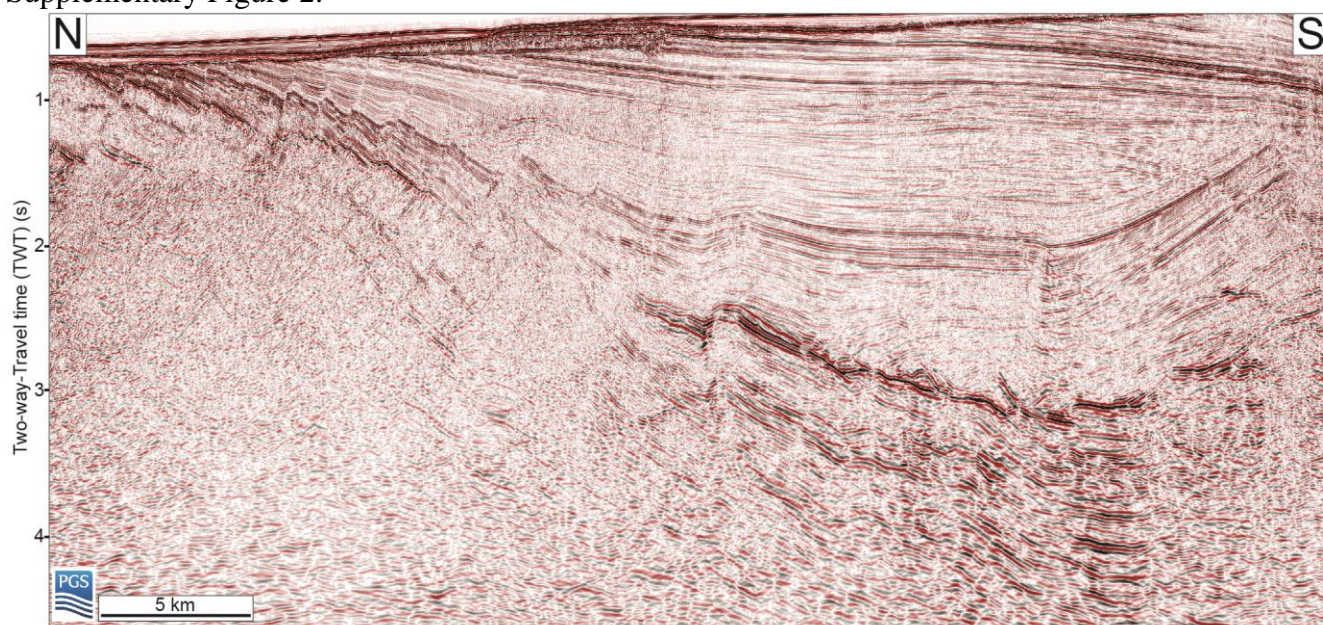
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346 Supplementary Figure 1.



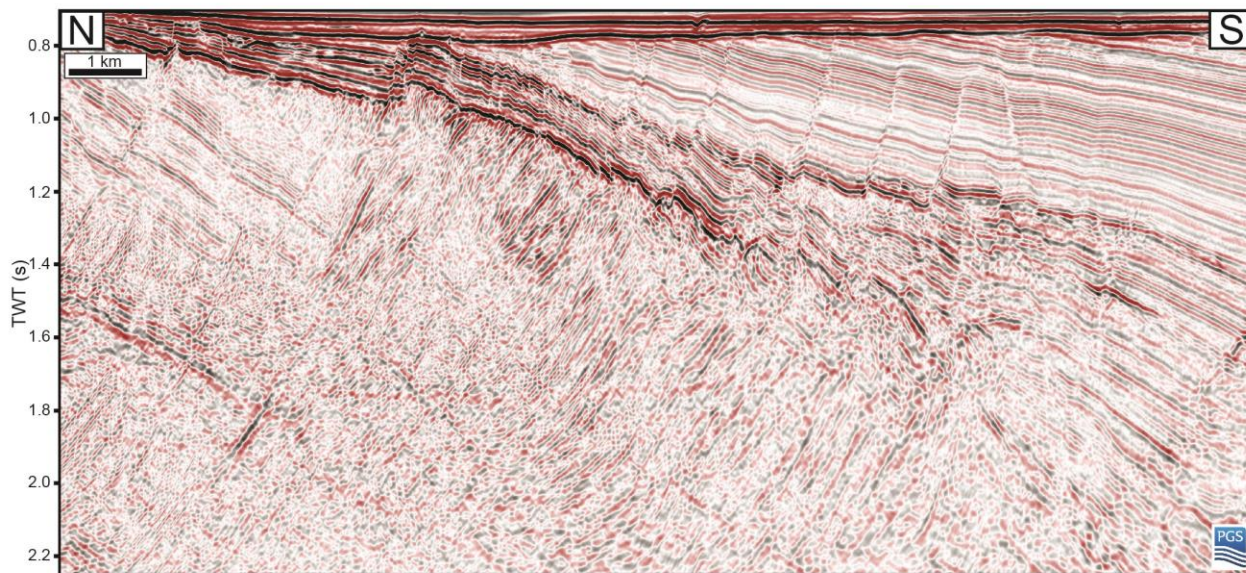
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350 Supplementary Figure 2.



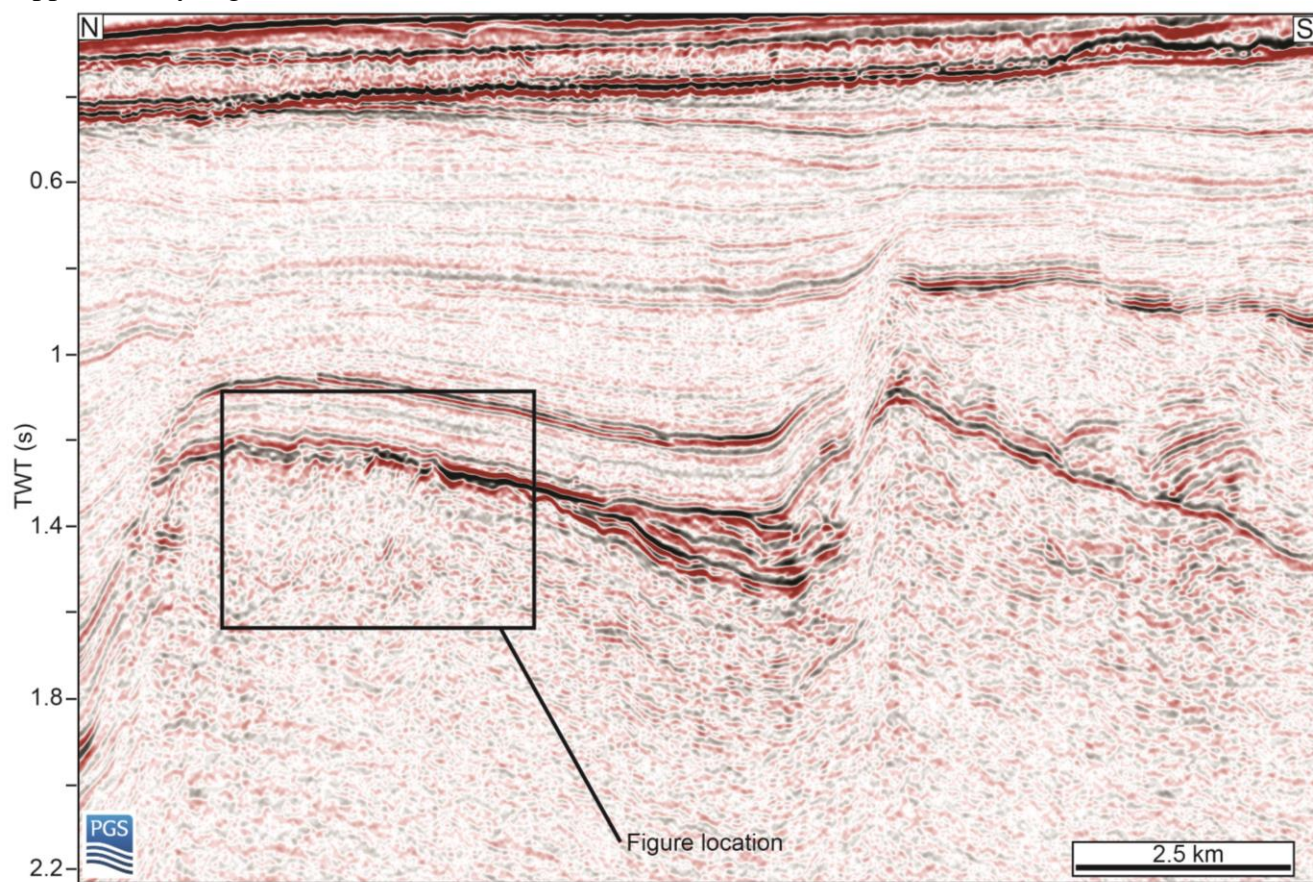
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354 Supplementary Figure 3.



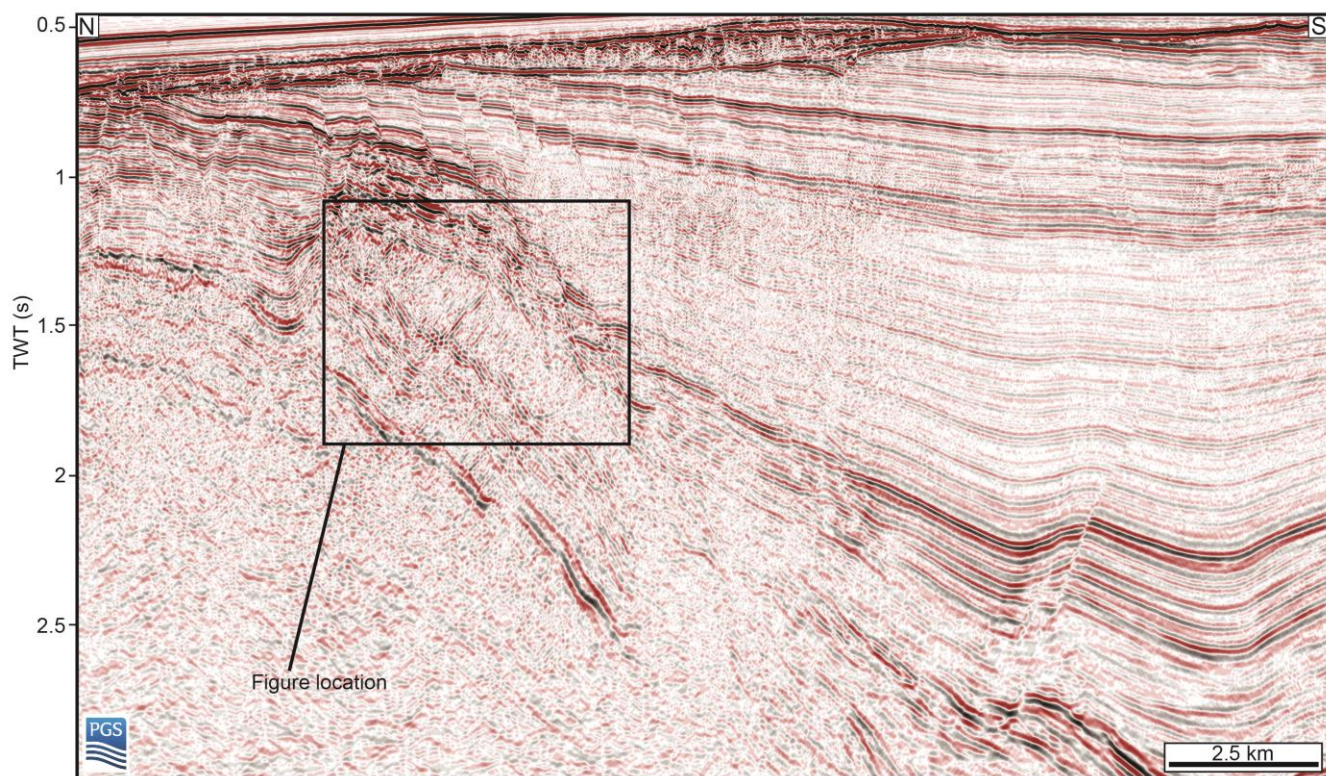
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358 Supplementary Figure 4



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363 Supplementary figure 5.



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367 Table S1
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TABLE S1										
Dataset	Data type	Acquisition year	Record length (ms TWT)	Streamer length (m)	Fold	Shot interval (m)	Polarity (SEG convention)	Processing steps		
MC2D FAB 2003	2D	2003	7000	6000	120	25	Reverse	2D SRME	Hi-Res Radon Demultiple	Kirchoff PSTM
MC2D DFB 2005	2D	2005	8000	6000	n/a	n/a	Reverse			
ST8629	2D	1986	6000	N/A			Reverse			
GFR-93	2D	1993	12000	4500			Reverse			
FB92	2D	1992	6000	N/A			Reverse			
SKAGRE96	2D	1996	7000	3000			Reverse			
NSR03-07	2D	2003-2007	9216	8087			Reverse			
ST9211	2D	1992	7000	3000			Reverse			
NH0504	3D	2005	4040	3000			Normal			
						SRME	Surface related multiple elimination			